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Stochastic optimization models for energy management in carbonization process of carbon fiber production

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HIGHLIGHTS

- Seven factors need to be considered simultaneously for energy optimization.
- Stochastic optimization model can be used for process control.
- Convex Hull method could model and predict the energy consumptions properly.
- MILP can optimize the energy consumptions in a given range of production quality.

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ABSTRACT

Industrial producers face the task of optimizing production process in an attempt to achieve the desired quality such as mechanical properties with the lowest energy consumption. In industrial carbon fiber production, the fibers are processed in bundles containing (batches) several thousand filaments and consequently the energy optimization will be a stochastic process as it involves uncertainty, imprecision or randomness. This paper presents a stochastic optimization model to reduce energy consumption a given range of desired mechanical properties. Several processing condition sets are developed and for each set of conditions, 50 samples of fiber are analyzed for their tensile strength and modulus. The energy consumption during production of the samples is carefully monitored on the processing equipment. Then, five standard distribution functions are examined to determine those which can best describe the distribution of mechanical properties of filaments. To verify the distribution goodness of fit and correlation statistics, the Kolmogorov–Smirnov test is used. In order to estimate the selected distribution (Weibull) parameters, the maximum likelihood, least square and genetic algorithm methods are compared. An array of factors including the sample size, the confidence level, and relative error of estimated parameters are used for evaluating the tensile strength and modulus properties.

The energy consumption and N_2 gas cost are modeled by Convex Hull method. Finally, in order to optimize the carbon fiber production quality and its energy consumption and total cost, mixed integer linear programming is utilized. The results show that using the stochastic optimization models, we are able to predict the production quality in a given range and minimize the energy consumption of its industrial process.

1. Introduction

Carbon fiber is finding growing applications as an engineering material due to its light weight, strength, and durable properties. In carbon fiber manufacturing, a precursor fiber undergoes significant chemical and physical changes through a series of thermal processing steps, including stabilization, pre-carbonization, and finally carbonization [1]. The carbonization step is particularly critical for the production of carbon fibers with a high tensile strength for high modulus fiber production and treatment by High Temperature (HT) furnaces [2]. Energy management of the HT furnace is becoming increasingly important because the energy consumption of this process step is around 9.1% of the total energy

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consumed in the production process. Energy management of the HT furnace can be broken into two key areas: furnace design and process energy reduction. In HT furnace design the following features should be considered: (i) the ability to rapidly purge and heat up the furnace, (ii) balancing of the gaseous atmosphere inside the furnace, (iii) careful choice of insulation materials to minimize heat loss, (iv) high efficiency with low N_2 consumption, and (v) an efficient fiber cooling system. Energy management of the HT furnace involves a number of parameters, which make it difficult to optimize the process. A promising approach to solve this problem is to use a rigorous model-based energy management process. A recent study [3] showed that during the carbonization of PAN-based carbon fibers, as the temperature increased the tensile strength decreased, and the modulus increased. Also the carbonization process must be carried out under an inert atmosphere and examination of fiber tensile strength and modulus showed a significant increase with carbonization treatment under nitrogen (N_2) gas [4]. To ascertain the optimum conditions that are required to produce high modulus and tensile strength carbon fibers, the pre-carbonized fibers are heated for several minutes in a HT furnace. It is important to note that optimization of energy in HT furnace should take into account the production quality and economic objectives by including those in the optimization criteria.

Due to the fact that the fibers being processed contain a large number of filaments (6000, 12,000 or 24,000 filaments in each tow, with up to 600 tows moving through a production line), the optimization of the process energy consumption involves uncertainty and is modeled as a stochastic process. The stochastic nature of the mathematical models stems from the fact that the mechanical properties of each filament within a fiber bundle are unknown and our knowledge of those can only be expressed in probabilistic terms (using a probability density function).

This suggests that a stochastic optimization model would be able to reduce energy consumption while meeting a given range of desired mechanical properties. Stochastic models are subsequently helpful in (i) the design of experiments [5], (ii) process control [6], (iii) optimizing manufacturing procedures [7], (iv) product reliability in measuring overall quality of products [8], (v) system identification in building mathematical models for forecasting and comparison [9], and finally (vi) improving energy efficiency [10].

Stochastic optimization has been widely used in industrial settings [10–12]. The mechanical strength of carbon fiber is a stochastic variable, which cannot be fully described with a single value, but more properly with a distribution function [13,14]. Hence for a complete description of the mechanical properties of carbon fiber, a distribution analysis is required. Weibull [13] developed a statistical theory of the strength of materials and Zwaag [14] showed that the Weibull theory provides a useful description of the intrinsic statistical variation in the fracture stress of filaments from high performance materials. The Weibull modulus in this theory is an important parameter, which controls among others the length dependence of the average fracture stress and the bundle efficiency. The Weibull modulus is not a material constant and instead reflects the shape of the defect population present in a material. Based on a Weibull model, Stoner et al. [15] investigated the effect of cross-sectional shape on tensile strength of pitch-based carbon fibers using extensive single-filament testing. They created a model based on physical principles that accounted for the uncertainties of the test method. The model was compared with simple Weibull distribution and a number of mixed distributions based on the Weibull. Asloun et al. [16] also analyzed the determination of the tensile strength of high strength carbon fibers and their gauge length dependence by means of the Weibull model. They verified the validity of the method for untreated as well as for surface-treated high strength carbon fibers.

Determining the relevant parameters of a distribution function by numerical iteration is an important yet tedious problem. Traditional evaluation methods to calculate distribution parameters are: the least squares, graphical, empirical, cumulative probability, moment, and maximum likelihood [17–19]. Although both the moment and maximum likelihood (involving iterative procedures) usually produce good results, traditional evaluation methods for Weibull are not satisfactory. As such, the genetic algorithm as an intelligent optimization algorithm is employed here to calculate the parameters for the distribution and its performance is compared with likelihood and least squares methods.

Problem overview:

Industrial producers such as carbon fiber manufactures needs to consider the following factors simultaneously:

(i) Identify and control the process parameters be involved in the production and also optimal design of experiments (DOE).
(ii) Investigate the energy losses during the production process.
(iii) Find the desired distribution function for mechanical properties since those mechanical properties are involved in a number of samples (in our case each fiber tow including 24,000 filaments).
(iv) Optimize the selected distribution parameters.
(v) Define the sample size, the confidence level, and relative error of estimated parameters for testing of mechanical properties.
(vi) Model the energy consumption and process parameters (in our case N_2 gas).
(vii) Optimize the energy consumption (in our case carbonization) process in given range of mechanical properties such as tensile and modulus.

For this purpose our methodology are as follows:

First: By analyzing the carbonization process, the important factors including HT furnace parameters, drive characteristics, and gas flow rate are identified and DOE is conducted using the Taguchi approach.
Second: The HT furnace energy loss is modeled using energy balance equation and measurements.
Third: Many samples from each condition are tested by Weibull, Normal, Logistic, T-Location-Scale, Rician (as standard statistical distributions see in Appendix A: Table A.1) and to verify the distribution goodness of fit and correlation statistics, Kolmogorov–Smirnov measure is used.
Fourth: In order to improve accuracy of the estimated distribution parameters, maximum likelihood, least squares and the genetic algorithm intelligent optimization method are applied.
Fifth: The sample size, the confidence level, and relative error of estimated parameters for testing of mechanical properties are tested by Monte-Carlo method.
Sixth: Energy and N_2 gas is modeled by the Convex Hull method.
Seventh: Mixed integer linear programming is used to optimize the energy consumption for the given target mechanical properties.

A variety of industrials processes, including those in the carbon fiber industry, would benefit from our results as those enable the proper adjustment of the process control parameters such as the power required to operate the process. The proposed stochastic optimization algorithm can potentially reduce the overall energy consumption as well.

The main contributions of this paper are as follows: